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DESIGN OF THE ADVANCED CARGO AIRCRAFT
THE U.S. ARMY'S NEXT GENERATION TRANSPORT ROTORCRAFT
AN OVERVIEW

by

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Summary

A family of rotorcraft were defined to meet the projected requirements of the U.S. Army for combat airlift in the year 2000 and beyond. A detailed definition of equipment and mission load inventories was developed, and a knowledge-based simulation assessed the capability of various-size aircraft to transport these inventories in three combat theaters: Europe, Southwest Asia, and Latin America. Payload capabilities of 18, 26, 30, and 39 thousand lb (8,165, 11,793, 13,608, 17,690 kg) with 270 nm (500 km) radius of action at Army hot day ambients were identified as potentially cost effective design points. A 9 X 9 ft (2.74 X 2.74 m) cabin cross section was required, with a cabin length of 32 to 41 ft (9.75 to 12.5 m) depending on design payload. Single and tandem rotor helicopter solutions were defined for each of the four design payloads. A tilt rotor solution was also examined. A single rotor configuration with a design gross weight of 94,000 lb (42,637 kg), a rotor diameter of 122 ft (37.2 m), and three engines served as a baseline for evaluation of the impact of various design criteria and system technology levels.

Analysis

The U. S. Army has identified a need to replace their existing medium lift cargo helicopters (CH-47s) with an Advanced Cargo Aircraft (ACA) that will enhance present combat airlift capabilities with increased payload capacity, increased range and survivability, and greater mission versatility, flexibility, and responsiveness. This new aircraft, presently scheduled for initial operational capability (IOC) in 2015, will support the goals of the Army of Excellence and will constitute an essential element of the Airland Battle Doctrine for the coming century. It will be required to transport a wide variety of loads under the stressful conditions of combat worldwide. The cornerstone of the ACA design must be its flexibility, versatility, and ease of handling a diversity of combat multipliers. It must be designed to provide the Army's tactical link to the Air Force's strategic lift capabilities, and to facilitate the timely transfer of necessary stores and supplies from the supply points down to the combat user levels. An effective ACA will be one that provides the local Commander freedom to determine what critical supplies are moved and where, based upon his on-the-spot assessment of user needs and the criticality of his missions. The ACA must be an effective combat multiplier itself, enabling the Commander to rapidly shift his assets in a way that brings about a positive and decisive outcome to the battle.

The Aviation Applied Technology Directorate (AATD) of the U. S. Army at Ft. Eustis, Virginia, contracted with Sikorsky Aircraft to conduct a study of ACA design requirements. The approach taken to define the best ACA design comprised three separate tasks: definition of airlift requirements, evaluation of a family of aircraft designs in simulated combat operations, and identification of needed technology exploitation.

In the first task, an assessment was made of the combat and combat service support airlift movement needs. This task included projection of the current vehicle and equipment inventory into the future operational time frame, definition of scenarios for several potential conflict intensity levels, and prediction of the relative frequency of movement needs. A listing of load items anticipated for rotorcraft transport in a year 2015 time frame was compiled from the inputs of 19 different U. S. Army organizations. Each load item was characterized by its weight, dimensions, whether it can be carried externally, whether it is stackable internally, and what its typical aircraft load and unload times are. Load items ranged from a 240-lb (109-kg) trooper to a 110,800-lb (50,258-kg) M-88 recovery vehicle.

Drawing from the compiled equipment list, eight general categories of missions were developed to represent future U.S. Army combat airlift requirements. Figure 1 provides examples of the selected missions, which ranged from combat resupply to the movement of outsized equipment. These missions were incorporated into three representative theaters of operation; Europe, Southwest Asia, and Latin America, to create a total of 24 unique missions. These theaters were selected based on the likelihood of future U.S. Army involvement, and provide a wide range of ambient conditions (Europe 2000 ft, 70°F (610 m, 21°C), Latin America 3000 ft, 85°F (914 m, 29°C), Southwest Asia 4000 ft, 95°F (1219 m, 35°C)). Detailed mission descriptions were then developed listing the load items, mission profiles, expected level of threat, and realistic operational constraints. The load item list for each mission included weight and dimensions as well as item quantity and a numerical ranking of item priority. Load item priority was ranked from 1 (lowest) to 9 (highest) based on the item's ability to impact the outcome of the battle or event. Mission flight profiles described mission leg lengths and headings and included features such as assembly areas, pickup points, air control points, drop-off points, and refuel support areas. Mission geometries were derived from actual geographical maps and included the impact of topographic features, existing airfields, harbors, and transportation infrastructure.

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The second task drew upon the results of Task I to create an expert system simulation model which helped determine cabin dimensions and payload capability which maximized vehicle productivity. The assessment of the performance of a large collection of aircraft sizes in the 24 missions required a new analysis tool to manage the large number of variables and combinations involved. A knowledge-based simulation was developed by software engineers at the United Technologies Research Center to model the rotorcraft cargo transportation task. Key elements of the transport task include the packing of the aircraft (how to most efficiently load individual items in a specified cabin size), flight routing, and fuel management. Rules were developed by logistics experts for each of these elements and were combined with the details of the 24 missions to create a realistic operational simulation. Features included the trading of fuel for additional payload if mission legs permitted, and an accounting of time and fuel spent in loiter awaiting availability of finite area landing zones. Detailed results are provided on an individual and aggregated mission basis, and include over 30 mission performance parameters describing the utilization, effectiveness, and efficiency of each vehicle size.

Three measures of effectiveness (MOE's) were selected to identify optimum sized aircraft. Ton-miles is a traditional MOE often used in cargo transport analysis. Simply the product of tons of cargo and number of miles traveled, this measure reveals nothing about the efficiency of the aircraft size in relation to the cargo items carried. The larger the aircraft the better. Specific productivity is another widely used MOE that normalizes ton-miles by dividing it by mission time and aircraft weight empty. Mission time reflects delivery speed, and weight empty is analogous to vehicle cost. Specific productivity therefore represents relative efficiency in delivering cargo.

While measuring efficiency, however, specific productivity provides no indication of the vehicle's effectiveness in carrying every load within a given mission. For example, analysis of the simulation output indicated that a relatively small ACA, although very efficient, carried only 75% of the cargo items listed for a mission due to its limited lift capability. A less efficient but larger ACA had a lower specific productivity, but delivered over 95% of the mission cargo. A new MOE termed priority effectiveness was developed and used along with specific productivity to identify both efficient and effective aircraft sizes. Priority effectiveness is the fraction of cargo items delivered weighted by their relative priority. It is the ratio of actually delivered priority value to that mission's available priority value. Thus, priority effectiveness penalizes a design that leaves uncarried loads behind and rewards a design that delivers a large percentage of high priority loads.

As a final measure, priority effectiveness is combined with specific productivity to provide an overall MOE, priority productivity, that captures the impact of both an efficiently sized aircraft and a mission effective aircraft. Figure 2 compares the results obtained using specific productivity with the corresponding priority productivity results. In this example an ACA with a 36,000-lb (16,329-kg) payload has a greater MOE value than one with an 18,000-lb (8,165-kg) payload because of its increased effectiveness in the mission. A new point of interest is also exposed at 30,000-lb (13,608-kg), as this size aircraft benefits from a jump in effectiveness but not in efficiency. In general, the effectiveness fraction tends to bias the selection towards the larger, more effective sizes. This bias decreases as payload capacity increases until either a priority effectiveness fraction of 1.0 or the maximum value of effectiveness possible for a particular cabin size is obtained. Table 1 provides a summary of the selected measures of effectiveness.

TABLE 1. SUMMARY OF MEASURES OF EFFECTIVENESS

MOE	Definition
Specific Productivity	$\dfrac{\text{cargo weight X miles carried}}{\text{mission time X empty weight}}$
Priority Effectiveness	$\dfrac{\text{priority value delivered}}{\text{priority value possible}}$

(where priority value = priority value X load item quantity)

Priority Productivity	specific productivity X priority effectiveness

One hundred and sixty combinations of payload capacity and cabin dimensions were evaluated in an initial optimization process using the knowledge-based simulation. Four locally optimum payload capacities were identified, and an optimum cabin cross section was selected. Simulation data were aggregated using the anticipated frequency of operation for each mission within a theater to create weighted average theater-level results. All-theater results were then derived using a weighted average of the three theater-level results.

Cabin lengths from 24 to 52 ft (7.3 to 15.8 m) and payload capacities from 14,000 to 40,000 lb (6,350 to 18,144 kg) were addressed in the initial run matrix. The 4000 ft, 95°F (1219 m, 35°C), 270 nm (500 km) radius of action payload capacities are used only as a common reference; the payload capacities are greater at less demanding ambient conditions and mission distances. A coupling between payload capacity and cabin length was clearly seen at about a 26,000-lb (11,793-kg) payload capacity. Beyond this, increasing payload capacity required an increased minimum cabin length to benefit from increased lift capability. Table 2 provides a listing of these payload capacity selections and their corresponding cabin lengths.

TABLE 2. FIRST ITERATION SIZE SELECTIONS

Payload capacity (4000 ft, 95°F)		Cabin Length	
(lb)	(kg)	(ft)	(m)
18,000	8,165	32	9.75
24,000	10,886	36	10.97
30,000	13,608	36	10.97
38,000	17,236	40	12.19

For each of the initially selected aircraft sizes in Table 2, cabin width and height were varied to identify any coupling relationships and to make preliminary selections. Using priority productivity, each size exhibited optimum capability at a cabin height of 102 in. (259 cm). The loads driving the cabin height selection were identified by the simulation to be a collection of wheeled vehicles including the HEMTT.

Similar data were compiled for cabin width. As was the case for height, each aircraft size was found to have the same optimum cabin width, 96 in. (244 cm). The cargo items driving the width selection were identified to be particular containers and pallets including the palletized loading system (PLS) flatrack and 20-ft (6.1-m) containers.

A cabin cross section was developed incorporating the selected dimensions. A military standard 6-in. (15-cm) clearance was provided above the load and between the side of the load and the cabin walls, making the resulting internal dimension 9.0 ft by 9.0 ft (2.74 m by 2.74 m). This cross section was used in all subsequent simulations and design studies.

A second series of simulations was conducted to complete the design optimization, with more rigorous analysis of locally optimum payload capacities and the corresponding optimum cabin lengths. Data were again collected on a mission level and aggregated to theater-level results.

The European missions generally feature medium-length mission legs and a large spectrum of cargo item sizes, with many items under 5,000 lb (2,268 kg) and many over 30,000 lb (13,608 kg). Trades of fuel for additional payload can be in excess of 10,000 lb (4,536 kg). Vehicle specific productivity is typically driven by combinations of cargo loads of several items and not by individual items. Aircraft payload capacity at the European ambients of 2000 ft, 70°F (610 m, 21°C) and the medium ranges is of the order of 150% of the reference 4000 ft, 95°F (1219 m, 35°C), 270 nm (500 km) radius of action payload capacity. Given the large payload capacity, typical aircraft sizes are volume-limited well before becoming lift-limited. Major peaks of performance were identified at 25,000-, 39,000-, and 50,000-lb (11,340-, 17,690-, and 22,680-kg) (4000 ft, 95°F) payload capacities with a minor local peak at 18,000 lb (8,165 kg).

The Southwest Asia missions feature very long mission legs with up to 270 nm (500 km) radii of action. These missions were also flown at the most stringent ambients, 4000 ft, 95°F (1219 m, 35°C). Rotorcraft airlift is seen as playing a major role in this theater due to the lack of a reliable transportation infrastructure, the result being large numbers of items of various types in the mission lists. Missions often require nine or more sorties of an eight-aircraft company to deliver all cargo. Aircraft sizes that can carry a greater number of items per load reduce the number of sorties required. The combination of long mission legs and high density altitude yield low payload capacities, and aircraft are frequently lift-limited before becoming volume-limited. The mission ranges required also discourage the use of external lift. Specific productivity peaks and levels off at 44,000 lb (19,958 kg) design payload, after which increasing aircraft weight empty reduces the specific productivity.

Latin America missions are typically short to medium in length and are flown at an intermediate ambient condition. The large variety of load items seen in the other theaters is reduced, such that individual cargo items can have a substantial impact. External lifts are frequently used and internal fuel is often reduced as much as 50% of fuel capacity, or 7,000 to 8,000 lb (3,175 to 3,629 kg). Local peaks in specific productivity occurred at 17,000-, 30,000-, 37,000-, and 46,000-lb (7,711-, 13,608-, 16,783-, and 20,865-kg) design payload. Each optimized payload requirement is the result of a specific additional capability that occurs at that point. At 17,000 lb (7,711 kg) a MILVAN becomes a viable load, at 30,000 lb (13,608 kg) the 20-ft (6.1-m) containers are transportable, at 37,000 lb (16,783 kg) efficiency jumps as certain double payloads become possible, and at 46,000 lb (20,865 kg) the long 48-ft (14.6-m) cabin increases internal lift capacity.

Each theater was assigned a weighting factor incorporating probability of utilization and intensity of conflict. Initial weighting set usage at 50% Europe, 25% Southwest Asia, and 25% Latin America. Using these theater weighting factors, individual theater results were combined into the all-theaters result shown in Figure 3. With these results the final payload capacity selections were made. Peaks identify locally optimum payload capacities at 18,000, 26,000, 30,000, and 39,000 lb (8,165, 11,793, 13,608, and 17,690 kg) at the 4000 ft, 95°F (1219 m, 35°C) ambient condition. Payload capacities beyond 42,000 lb (19,051 kg) were not considered due to the unrealistic aircraft sizes that result. Optimum cabin lengths were selected by varying cabin length for each selected payload capacity. A 32-ft (9.75-m) cabin length was selected for the 18,000-lb (8,165-kg) payload capacity aircraft. Both the 26,000-lb (11,793-kg) and 30,000-lb (13,608-kg) solutions require a 35-ft (10.67-m) cabin, and a 41-ft (12.5-m) cabin was matched to the 39,000-lb (17,690-kg) size.

Once optimum cabin size and payload lift capability were determined by the simulation, several "families of designs" were created to address conceptual design considerations. Table 3 summarizes the selected payload capacities and cabin dimensions for the family of ACA designs. Also listed is priority effectiveness for each of the selected sizes. This value represents the weighted average across all missions and all theaters. The payload capacity dictates the installed power and dynamics system sizing and the cabin dimensions define the fuselage geometry. These data were used to establish more detailed design solutions at each aircraft size for the purpose of down-selecting to a recommended ACA size.

Detailed designs were created for single, tandem, and tilt rotor solutions. Several design criteria were prescribed to ensure a level of commonality between the four selected design points. A design mission with a 270 nm (500 km) radius of action at 4000 ft, 95°F (1219 m, 35°C) was used. Figure 4 shows the design mission profile. Aircraft equipment requirements were provided by the Army or were established in communications with military personnel familiar with cargo aircraft operations. Key ACA operational and systems requirements include health monitoring and two-level maintenance capability, all-weather-day/night operations, extensive survivability and self-defense suites, and advanced load handling equipment.

TABLE 3. ACA SELECTED SIZES - SECOND ITERATION

Payload at 4000 ft, 95°F (lb/kg)	Cabin Length (ft/m)	Cabin Width (ft/m)	Cabin Height (ft/m)	Priority Based Mission Effectiveness
18,000 (8,165)	32 (9.75)	9 (2.74)	9 (2.74)	76%
26,000 (11,793)	35 (10.67)	9 (2.74)	9 (2.74)	84%
30,000 (13,608)	35 (10.67)	9 (2.74)	9 (2.74)	89%
39,000 (17,236)	41 (12.50)	9 (2.74)	9 (2.74)	93%

A maximum main rotor disk loading of 10 psf (478.8 nt/sq m) was mandated to permit unrestricted operations by ground personnel in the rotor downwash. A 1.75g normal load factor capability at 150 kts (278 kph) was provided. The fuselage and landing gear were designed to stringent UH-60 levels of crashworthiness.

Aerodynamic and weights technology levels were representative of 1990 state-of-the-art design. Extensive use was made of composite structure in both the fuselage and dynamic system. Drive system technology levels were derived from design efforts in a NASA-sponsored Advanced Rotorcraft Technology (ART) transmission program. A survey of current and future engine technology programs resulted in the selection of 6000 shp (4474 kw) class turboshaft engines.

Figure 5 shows the profile view of the ACA single rotor family of designs. The Lockheed C-130 transport and the CH-53E are shown for scale. Single rotor design solutions have gross weights ranging from 75,500 lb (34,246 kg) for the 18,000-lb (8,165-kg) payload size, to 126,600 lb (57,424 kg) for the 39,000-lb (17,690-kg) payload size. The two smaller designs use three 6000 shp (4474 kw) class engines while the larger designs use four. The 18,000- and 30,000-lb (8,156- and 13,608-kg) payload aircraft have disk loadings of 10 psf (478.8 nt/sq m), whereas the other designs required a reduction in disk loading to match hover power required with power installed. All designs employ a canted tail rotor which provides from 2,000 to 3,000 lb (907 to 1,361 kg) of vertical lift.

Tandem rotor design solutions were developed using identical design criteria as for the single rotor designs to the extent possible. Configuration commonality was maintained between families of designs by using the same cockpit, cabin section (where possible), and systems. All tandem rotor designs utilized four-bladed rotors, a 30% rotor overlap-to-diameter ratio, and a 0.15 gap-to-stagger ratio. Figure 6 depicts the resultant family of tandem rotor helicopter designs. The result of greatest interest when comparing single and tandem rotor designs was the similarity in gross weights at each design point. The tandem rotor designs typically have slightly lower weight empty which is balanced by increased fuel requirements. Simulation-selected sizes based on single rotor trending should therefore be generally applicable to tandem rotor designs as well. As in the single rotor designs, the two larger tandems use four engines and the 26,000- and 39,000-lb (11,793- and 17,690-kg) payload sizes require reduced disk loadings to match powers.

A tilt rotor design provided gains in mission productivity where internal loading and long mission legs permitted it to take advantage of higher speed capability, but its significantly higher weight, installed power, and disk loading make it an unattractive ACA solution.

Takeoff gross weight capability for the mission simulation was based on hover out of ground effect at 95% intermediate rated power (IRP) with a 200 fpm (1.0 mps) vertical rate of climb at the appropriate ambient conditions. The mission performance benefits of using takeoff techniques other than a standard hover were assessed by calculating payload capabilities for a variety of takeoff procedures. Techniques included rolling takeoffs, a hover takeoff using a higher short-term engine rating, and twin lift using two aircraft to lift a single very heavy external load. Individual takeoff techniques were matched to particular missions based on their suitability. For example, rolling takeoffs were used only with internal loads and where a runway was available, and twin lift was not used in high threat environments.

Figure 7 shows the impact of the use of alternate lift techniques on the overall priority effectiveness of the four sizes of aircraft. Using alternate lift the 39,000-lb (17,690-kg) payload size becomes 100% effective, being able to lift every item in every mission load list, including the the 110,800-lb (50,258-kg) M-88 recovery vehicle, which is twin-lifted in Europe. The 30,000-lb (13,608-kg) payload aircraft becomes over 99% effective, leaving only four loads behind. The greatest gains in effectiveness are realized at the 26,000-lb (11,793-kg) size, where effectiveness jumps from 84% to 98.5%. The smallest size shows substantial gains as well. The use of an aircraft size which is well matched for all but a few loads but can then transport those loads using special mission tactics, is seen as a substantial cost saving opportunity.

Selection of a recommended solution from the family of ACA designs involved evaluation of technical risk, procurement and life-cycle costs, and mission effectiveness. Given the high mission effectiveness achievable with the 26,000-lb (11,793-kg) payload aircraft using suitable alternate lift techniques, it was concluded that this aircraft provided the most attractive solution.

The study resulted in the following conclusions:

1. Eighty-five percent of the individual loads requiring airlift in support of U.S. Army intra-theater combat weigh less than 50,000 lb (22,680 kg). When frequency of need is considered, 90% of required mission loads weigh less than 30,000 lb (13,608 kg). The loaded PLS flatrack, in the 30,000-lb weight class, is a key driver of aircraft payload and cabin volume requirements.

2. A cost-effective aircraft size corresponds to the capability to take off vertically with 26,000 lb (11,793 kg) of payload, plus fuel for 270 nm (500 km) radius of action, at 4000 ft, 95° F (1219 m, 35°C). At sea level standard day and short ranges, lift capability is in excess of 50,000 lb (22,680 kg).

3. When rolling takeoff, use of a higher engine rating for takeoff, or twin lift (two aircraft acting together to lift a single load) is operationally viable, the already small number of non-liftable mission loads is reduced significantly.

4. The aircraft cabin should have an internal cross section of at least 9 x 9 ft (2.74 x 2.74 m), and an unobstructed length of at least 35 ft (10.67 m).

5. A helicopter meeting the above requirements with 1990 advanced level technology would have a design gross weight on the order of 94,000 lb (42,637 kg), and require three engines in the 6,000 hp (4,474 kw) class.

6. Single rotor and tandem rotor helicopter solutions provide about the same mission productivity for about the same weight and cost. Other attributes would have to be considered to discriminate between them.

7. The modest improvement in overall productivity that is potentially achievable with a tilt rotor would not appear to justify the higher weight, greater installed power, and harsher downwash environment.

8. A three-engine helicopter solution provides the most efficient match of total and engine-out power requirements. A larger engine should be considered for aircraft sizes requiring more than three 6000 shp (4474 kw) class engines.

9. Technology beyond what is currently in production is needed to produce an ACA with reasonable weight and cost. Without this technology, aircraft weight would increase on the order of 17%, or 16,000 lb (7,257 kg). The key areas where technology advances need to be concentrated are composites, transmissions, rotors, and engines.

10. Judicious application of technology that is advanced beyond the levels assumed, and selective tailoring of design criteria, should make it possible to reduce the weight of the aircraft by approximately 8,000 lb (3,629 kg). The key technology is advanced composites for the airframe and rotors. The key design criteria is the engine power rating assumed to be available for takeoff.

CATEGORY	EXAMPLE	SAMPLE CARGO LOAD	
COMBAT RESUPPLY Class V + Equipment	SHIFT COMBAT POWER AMMO & ARTILLERY	PALLETS W / AMMO	
CLASS III MOVEMENT Aviation Fuel	FARP RELOCATION	BLADDERS & PALLETS	
PERSONNEL	INFANTRY COMPANY RELOCATION	108 TROOPS W / WEAPONS	
VEHICLE MOVEMENT	AIR DEFENSE SYSTEM RELOCATION	LIGHT VEH. W / CREW	
RECOVERY OF EQUIPMENT	RECOVER DAMAGED AH-64 HELICOPTER	EQUIPMENT & CREW	
DEEP BATTLE	RESUPPLY ISOLATED COMBAT FORCE	PALLETS & TROOPS	
MEDICAL MISSIONS	RELOCATE MASH UNIT	PLS, SHELTERS & CONTAINERS	
OUTSIZED EQUIPMENT	GAP or OBSTACLE CROSSING	ENGINEER EQUIPMENT	

Figure 1. Eight catagories of U. S. Army cargo missions.
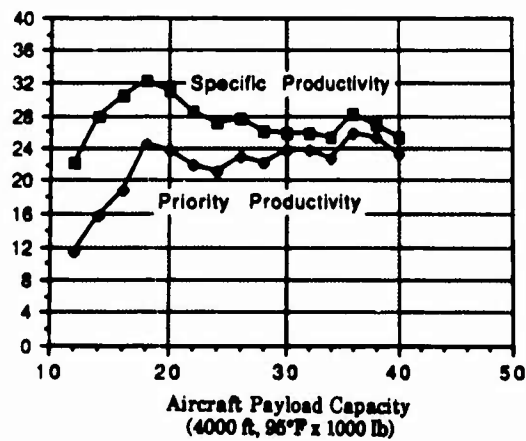
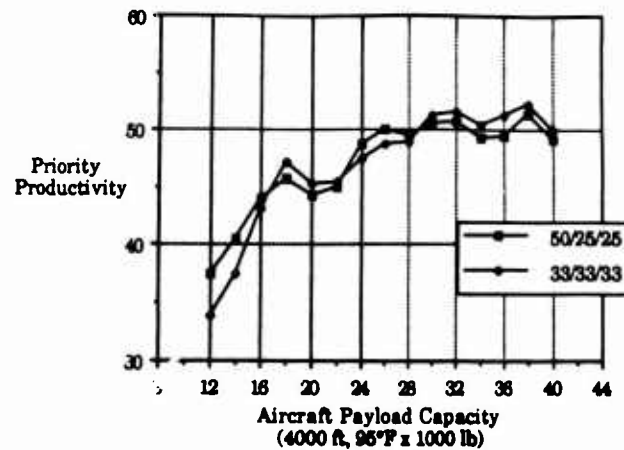Figure 2. Impact of mission effectiveness on specific productivity.

Figure 3. Impact of theater weighting factors on priority productivity.
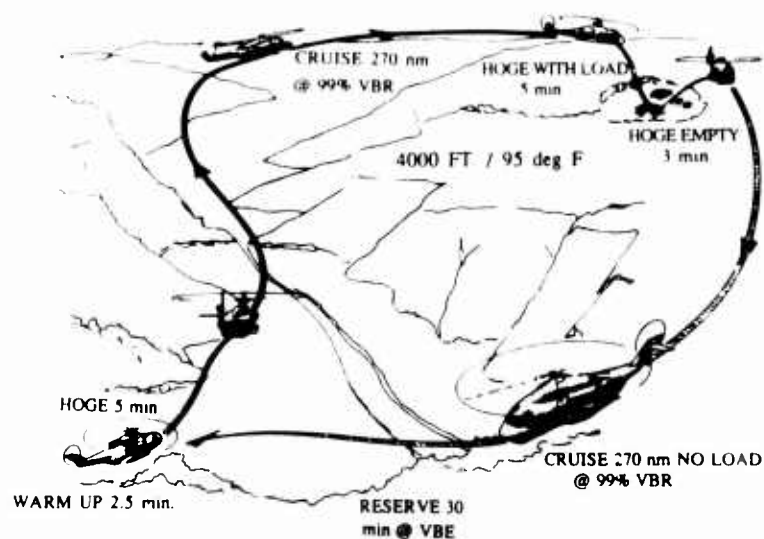
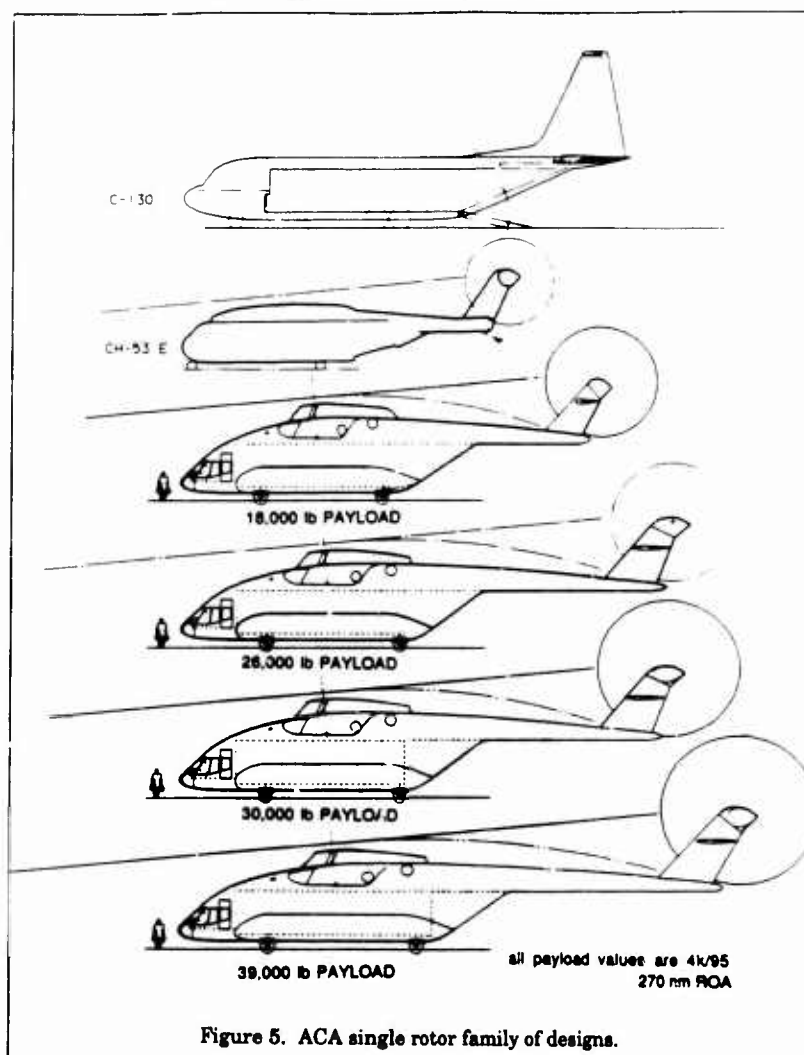Figure 4. ACA design mission.
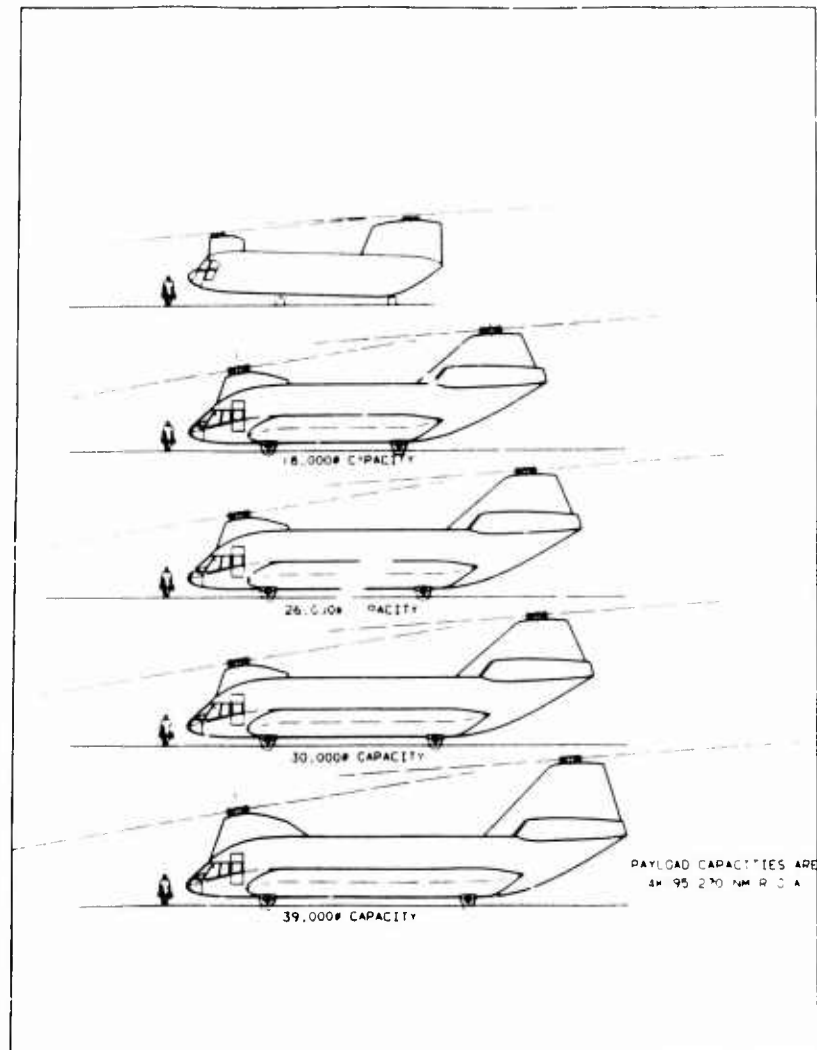

Figure 5. ACA single rotor family of designs.
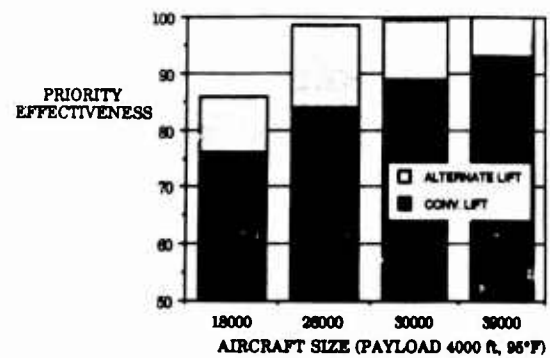
Figure 6. ACA tandem rotor family of designs.

Figure 7. Impact of alternate lift techniques on effectiveness.